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Prioritising potential incursions for contingency planning: pathways, species, and sites in Durban (eThekwini), South Africa as an example

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Abstract

Increased trade and travel have resulted in an increasing rate of introduction of biological organisms to new regions. Urban environments, such as cities, are hubs for human activities facilitating the introduction of alien species. Additionally, cities are susceptible to invading organisms as a result of the highly altered and transformed nature of these environments. Despite best efforts at prevention, new incursions of alien species will occur; therefore, prioritising incursion response efforts is essential. This study explores these ideas to identify priorities for strategic prevention planning in a South African city, Durban (eThekwini), by combining data from alien species watch lists, environmental criteria, and the pathways which facilitate the introduction of alien species in the city. Three species (with known adverse impacts elsewhere in the world) were identified as highly likely to be introduced and established in Durban (*Alternanthera philoxeroides*, *Lithobates catesbeianus* and *Solenopsis invicta*). These species are most likely to enter at either the Durban Harbour; pet and aquarium stores; or plant nurseries and garden centres – therefore active surveillance should target these sites as well as adjacent major river systems and infrastructure. We suggest that the integrated approach (species, pathways, and sites) demonstrated in this study will help prioritise resources to detect the most likely and damaging future incursions of alien species.

Keywords

biological invasions, early detection, incursion response planning, prioritisation, alligator weed, southern sandbur, American bullfrog, red imported fire ant

Introduction

Human-related activities such as trade and travel have facilitated the increased introduction of biological organisms outside their native range (Hulme 2009, Tatem 2009, Faulkner et al. 2016a, Hill et al. 2016). Introduction of alien species (sensu Richardson et al. 2000) to regions outside their native range is a serious problem which can result in the loss of biodiversity, and have negative economic and social impacts (Lövei 1997, Pimentel et al. 2001, Kenis et al. 2009, Vilà et al. 2010, Vilà et al. 2011). However, not all alien species pose an unacceptable risk of becoming invasive and many have significant benefits. Moreover, the capacity to respond to the threat of biological invasions is limited, severely so in some cases (Early et al. 2016). It is thus impractical and even undesirable to prevent every alien species from being introduced into a new region. For these reasons, efforts to prevent biological invasions need to be prioritised.

McGeoch et al. (2016) suggest that prioritisation should incorporate three aspects – species, pathways, and sites. Specifically for prevention, priority should be given to species posing the greatest risk of invading new regions, the pathways facilitating their introduction, and sites most at risk of being invaded. For example, species can be assigned to watch lists based on pre-border risk assessments that inform prevention strategies and contingency plans (Genovesi and Shine 2004; Faulkner et al. 2014, Nehring and Klingenstein 2008, Parrot et al. 2009). The German-Austrian Blacklist System (GABLIS), one such example, assigns species to three different categories based on risk assessments: 1) species that are of concern and for which specific intervention is required; 2) species whose risk to biodiversity cannot be ascertained; and 3) species with no risk to biodiversity that can be imported (Essl et al. 2011). GABLIS is a fairly rapid and effective assessment of different taxonomic groups in a variety of environments and illustrates the benefits of using watch lists as an early warning system (Essl et al. 2011, Verbrugge et al. 2010). Similar approaches have been implemented in Germany ('warn list' for aquatic alien species – Nehring and Klingenstein 2008), Belgium (Branquart 2007) and South Africa (NEMBA prohibited species list – DEA, 2016; watch list of alien species – Faulkner et al. 2014).

Similarly, pathways facilitating the introduction of alien species to new regions need to be identified and the risk associated with introductions facilitated through these pathways assessed. Priority should then be given to the pathways of introduction which pose the highest risk of facilitating the introduction of alien species (Padayachee et al. 2017, Pergl et al. 2017). The aim of this approach is to reduce colonisation pressure (i.e., the number of alien species) and propagule pressure (i.e., the number of individuals of a given alien species) facilitated through high risk pathways of introduction (Hulme et al. 2008, Reaser et al. 2008). This approach is significant in targeting the prevention of multiple taxa being introduced to a variety of environments, and especially in responding to the unintentional introduction of alien species.

Finally, sites are assessed as high-risk based on the likelihood of an invasion (i.e., the exposure to incursions and whether incursions will establish themselves and become invasions) and sensitivity (i.e., most vulnerable to the impacts of invasions) (Wil-

son et al. 2017). Sites which are most at risk of being invaded and most sensitive to the impacts of invasions are given priority for targeting the surveillance of new alien species. An important consideration in prioritising sites for prevention efforts is to identify where species are likely to first be introduced and established. In this context, and given the preponderance of introduction pathways, it is important that some biosecurity efforts explicitly focus on cities. Cities can be considered as sites where invasions are likely to occur as a result of the high environmental heterogeneity, high transport intensity and high levels of disturbance present in these environments (Cadotte et al. 2017; Gaertner et al. 2017; Kowarik 2011; Kuhman et al. 2010; Pyšek et al. 2010). Moreover, cities are potentially sensitive if the impacts affect ecosystem services or humans directly (Hansen and Clevenger 2005; Potgieter et al. 2017). They are also often areas where there are many complex competing demands on natural resource managers [e.g. (Dickie et al. 2014) and for South Africa see (Gaertner et al. 2016; Irlich et al. 2017; Zengeya et al. 2017)].

In this study we identify potential future incursions in Durban (eThekwini), South Africa, based on selected alien species, the pathways facilitating their introduction, and the sites most at risk of being invaded by these species. By jointly considering species, pathways, and sites, we aim to provide a tool for decision makers to more effectively target surveillance and contingency planning.

Methods

The eThekwini municipality is one of the largest port cities on the east coast of the African continent and is an important economic centre in South Africa (Roberts 2008). In addition to being a major populated city (approximately 3.4 million – STATSSA, 2017), eThekwini is also a significant contributor to tourism (Roberts 2008). Resources to target the introduction of alien species are scarce; therefore prioritisation is essential to effectively respond to the introduction of alien species.

To develop a methodology for decision makers to assign priorities for prevention strategies we: 1) identified cities with a similar climate to eThekwini; 2) used existing lists of species considered as not present in South Africa that pose an unacceptable risk of invasion; 3) identified which of the selected species are likely to have pathways facilitating their introduction to eThekwini; 4) developed climatic suitability models for the selected species based on the climate in eThekwini; and 5) linked the climate and pathway information to identify sites within eThekwini that should be the focus of contingency planning for particular species (Figure 1).

Human population, as a result of the associated activities (trade and travel), is one of the main correlates of species introductions into regions outside of their native range (Hulme 2009, Carpio et al. 2016), while climate is one of the main limitations to species establishment in these new regions (Rejmánek and Richardson 1996, Welk et al. 2002, Robertson et al. 2004, Thuiller et al. 2006). The methodology used in this study is required to be easily implementable and adjustable to various urban con-

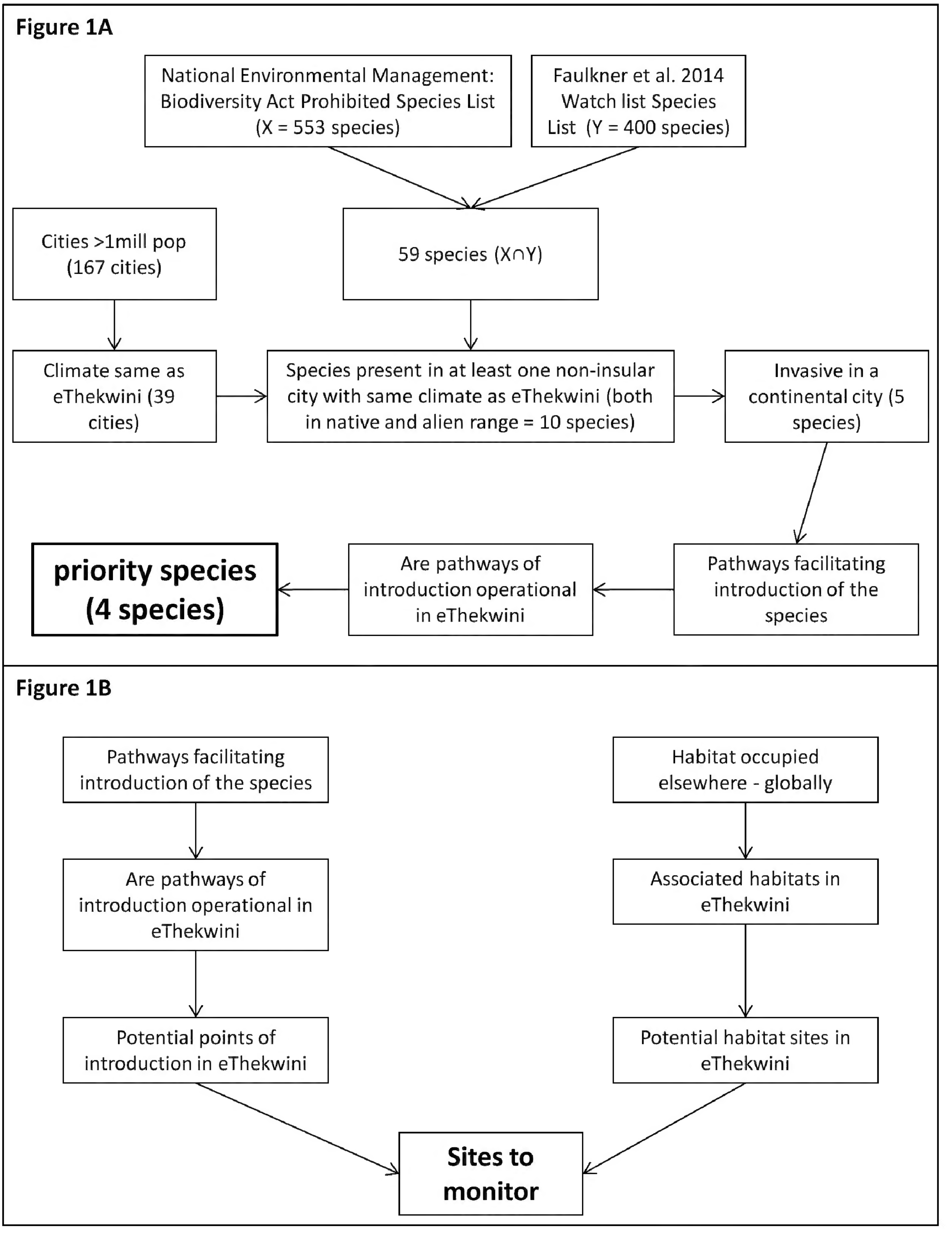

Figure 1. A simple and rapid method to prioritise targets for contingency planning to prevent biological invasions. The method identifies priority sites for managing particular high-risk incursions. **A** Shows the selection criteria used to select target species for climatic suitability analyses, with the number of species selected at each stage of selection indicated in parentheses. **B** Shows the criteria used to identify potential points of introduction for the select target species, as well as the criteria used to identify potential points of naturalisation, i.e. priority sites for monitoring in the eThekwini municipality.

texts; therefore we considered cities across countries with varying economic statuses. We selected global cities with populations of >1 million people (Padayachee et al. 2017) and used climate-matching techniques to select cities, from this list, with the same climate type as eThekwini based on the Köppen-Geiger climate classification (Kottek et al. 2006).

The National Environmental Management: Biodiversity Act (No. 10 of 2004) governs all biodiversity related issues in South Africa, including biological invasions (NEMBA, 2014). In regulations under NEMBA, a prohibited species list was created, based in part on expert opinion, that lists species that are not believed to be present in South Africa and whose introduction should be prevented (DEA, 2016). The implication is that strategic prevention plans should be developed for all species on the prohibited list. Separate to this, Faulkner et al. (2014) created a watch list of alien species whose introduction into South Africa should be regulated (based on likelihood of introduction, likelihood of establishment, and impact elsewhere). In this study we considered species present on both of these lists, as these are species that have been identified as high-risk and the regulations mandate government entities (e.g. municipalities) to manage such species.

We used these national lists and applied our own selection criteria (Figure 1) to identify species which should be prioritised for eThekwini. We ascertained the native and alien range of species using the CABI Invasive Species Compendium database (CABI 2017 – https://www.cabi.org/isc/) and the Global Register of Introduced and Invasive Species database (GRIIS 2017 – http://www.griis.org/). We downloaded occurrence data for all the species in both their native and alien range from the Global Biodiversity Information Facility (GBIF 2017a, b, c, d). Species occurrences for which sources were not listed, or were listed as "unknown" in the GBIF database, were removed from the dataset; additionally (for plant species) we removed occurrences based on herbarium records. Species with inconsistent taxonomic classification were also excluded (i.e., species for which variations and subspecies were only listed in GBIF). The occurrence records were then mapped and converted to shapefiles using ESRI ArcMap 10.3.1 software (ESRI 2015). Species occurrence records were then overlaid on to the selected cities. Species which occurred within the topographical boundaries of cities with the same climate as eThekwini were selected (regardless of whether the species were native or alien to the city). Furthermore, we excluded species which were only found as alien on islands (including Australia). This was on the assumption that biotic resistance is different on islands and continents. We then selected species present (as either native or alien) in cities with the same climate as eThekwini. We used the CABI Invasive Species Compendium (CABI 2018 – https://www.cabi.org/isc/) and Global Invasive Species Database (GISD 2018 – http://www.iucngisd.org/gisd/) to identify the pathways facilitating the introduction of the remaining species to see if they might be introduced to eThekwini. The description of the pathways used in this study was as per the Convention of Biological Diversity pathway classification scheme (Harrower et al. 2017; Hulme et al. 2008; Scalera et al. 2016) .

Maximum entropy distribution modelling was selected to map the potential geographic distribution and evaluate the risk of invasion of the remaining species (Maxent v3.4.1 – Phillips et al. 2006, Phillips et al. 2008). Even though Maxent has limitations in its representation as being a "presence-only data" algorithm, the software by default selects pseudo-absences in the form of background data and hence works well for presence-only datasets, such as the datasets downloaded from GBIF and used in this study (Barbet-Massin et al. 2012). Furthermore, predictions are robust as small sample sizes and irregularly sampled data do not strongly affect the model produced (Pearson et al. 2007, Elith et al. 2011). We chose to primarily utilise the default settings used by Maxent: 1) 10 000 random background points were assumed to be pseudo-absences points, however, we restricted the selection of background points to select points from the species distribution range (native and alien); 2) create response curves to evaluate the species response to individual predictors; 3) use a logistic output to produce continuous maps and 4) perform a jack-knife procedure to assess individual predictor importance to the model. In addition, we also chose to select auto features as these produced smooth response curves. We opted to change the following settings: 1) we controlled over-fitting and clamping by setting the regularisation parameter to 1; 2) we evaluated the model and reduced bias by setting a random seed and selecting a random test percentage of 25 percent (i.e., the model was trained using 75% of the data); 3) we ensured variability by choosing to subsample the data over 10 replicate models; and 4) we allowed the model enough time for convergence by setting the number of iterations to 5000. The importance of individual bioclimatic predictors was assessed using jack-knife procedures and their individual percentage contribution to training the model. We evaluated model performance using a measure of model performance called the area under the curve (AUC) of the receiver operating characteristic, ranging from 0 to 1 (high accuracy = AUC > 0.9; moderate accuracy = 0.9 < AUC > 0.7; poor accuracy = 0.7 < AUC > 0.5; model performance worse than random = AUC < 0.5) (Peterson et al. 2011). We created binary maps of the species predicted climatic suitability using ESRI ArcMap 10.3.1 (ESRI, 2015). Climate is one of the main determinants of species growth and establishment in regions outside their native ranges (Welk et al. 2002, Robertson et al. 2004, Thuiller et al. 2006, Ficetola et al. 2007); therefore we utilised climatic data from the WORLDCLIM database (19 bioclimatic predictors – http://www.worldclim.org/) (Hijmans et al. 2005). We selected bioclimatic predictors which were closely related to the successful growth and establishment of the selected species (e.g. *Lithobates catesbeianus* thrives in wet, hot environments, therefore we selected precipitation of the warmest month as a climatic variable), and those predictors which were least correlated. We tested the multicollinearity of the data for each species using the correlation and summary statistics tool found in the SDM toolbox developed for ESRI ArcMap (Brown, 2014). The SDM toolbox was developed to facilitate the pre-processing of data for species distribution modelling, specifically using the Maxent software (Phillips et al. 2008, Brown 2014). The correlation between raster layers is measured as the dependency between all of the input layers. Correlation was measured as a ratio of the covariance between the raster layers divided by the product of their standard deviations. We set a correlation cut-off value of 0.60 (i.e., layers with a correlation of 0.60 or higher were considered as

being highly correlated) (Snedecor and Cochran 1968, Brown 2014). Layers which were highly correlated were excluded from the climatic models.

Results

Fifty-nine species were on both the NEMBA prohibited species list and the watch list produced by Faulkner et al. (2014) (invertebrates – 9, plants – 32 and vertebrates – 18). Based on the Köppen-Geiger Climate Classification (Köttek et al. 2006), there are 39 cities of over a million inhabitants which have the same climate type as eThekwini (Suppl. material 1). Ten species, from the initial 59, were present in at least one of the 39 cities. After eliminating species which were only alien or invasive on islands, five species were left (*Alternanthera philoxeroides* – alligator weed, *Cenchrus echinatus* – southern sandbur, *Lithobates catesbeianus* – American bullfrog, *Solenopsis invicta* – red imported fire ant, and *Vulpes vulpes* – red fox).

We identified the pathways of introduction for each of the remaining species. At this stage, we excluded *V. vulpes* (red fox) as it is extremely unlikely to be introduced by the only pathways that have historically led to its introduction to other countries (hunting in the wild and fur farms – GISD, 2018). The pathways facilitating the introduction of *C. echinatus* were unknown (GISD, 2018). This meant that while it was possible to still build a climatic suitability model for the species, it is not possible, at this stage, to link climate suitability to introduction pathways (Box 2). *Alternanthera philoxeroides* (Box 1) and *S. invicta* (Box 4) have previously been introduced through the transport-stowaway and transport-contaminant pathways. The introduction of *L. catesbeianus* (Box 3) has been facilitated through the release and escape pathways. Three main potential points of introduction were identified for these species based on the pathways: the Durban Harbour (all four species), pet and aquarium stores (29 within the municipal boundary – *L. catesbeianus*) as well as plant nurseries and garden centres (60 within the municipal boundary – *S. invicta*). We then identified likely points of first naturalisation as sites to monitor for the presence of the three species: the Durban Harbour was identified as a site to monitor for the presence of *A. philoxeroides* (Figure B1) and *S. invicta* (Figure B4). River systems adjacent to points of introduction are also identified for surveillance efforts for *A. philoxeroides* (Figure B1), *L. catesbeianus* (Figure B3) and *S. invicta* (Figure B4) because of these species' dependency on readily available water resources for survival. We also identified the built infrastructure surrounding the Durban Harbour for monitoring for *S. invicta* (Figure B4). River systems and wetlands adjacent to pet and aquarium stores were identified for monitoring for the presence of *L. catesbeianus* (Figure B3).

Species distribution models

The climate models developed for the selected species ranged from highly accurate model performance to moderately accurate performance based on the AUC of receiver

Box 1. Pathways of introduction, preferred habitats, potential entry points, sites to monitor, and climatic suitability for *Alternanthera philoxeroides* (alligator weed).

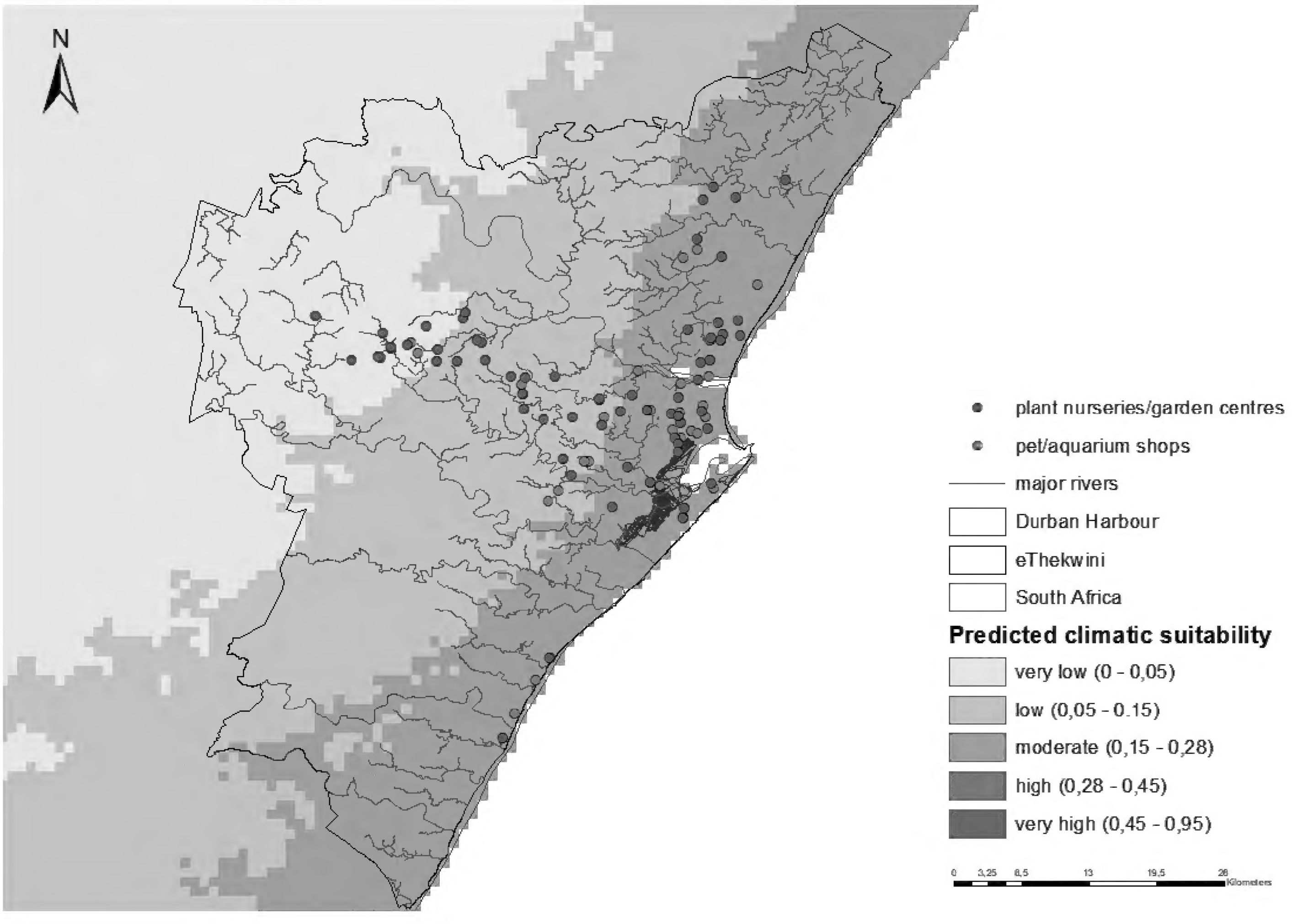

Figure B1. Predicted climatic suitability *A. philoxeroides* in Durban. The model is highly accurate in predicting climatic suitability (0.929 ± 0.007 – AUC±SD). Predicted suitability is indicated using a colour scale (darker shades indicate higher predicted suitability). Also indicated are the potential points of introduction and potential points of first naturalisation to monitor for *A. philoxeroides* in Durban.

Pathways of introduction: Ship ballast (historical), transportation of habitat material, ornamental purposes

Potential points of first introduction: The Durban harbour, plant nurseries and garden centres, pet and aquarium shops

Habitat and Land uses: *Alternanthera philoxeroides* can grow in a variety of habitats but is usually found in aquatic habitats, particularly rivers, lakes, dams, ponds, canals, flood plains and irrigation channels

Habitats present in Durban: Yes

Potential sites of first naturalisation in Durban: The Durban harbour and adjacent river systems (particularly uMhlatuzana and uMbilo river systems)

Box 2. Pathways of introduction, preferred habitats, potential entry points, sites to monitor, and climatic suitability for *Cenchrus echinatus* (southern sandbur).

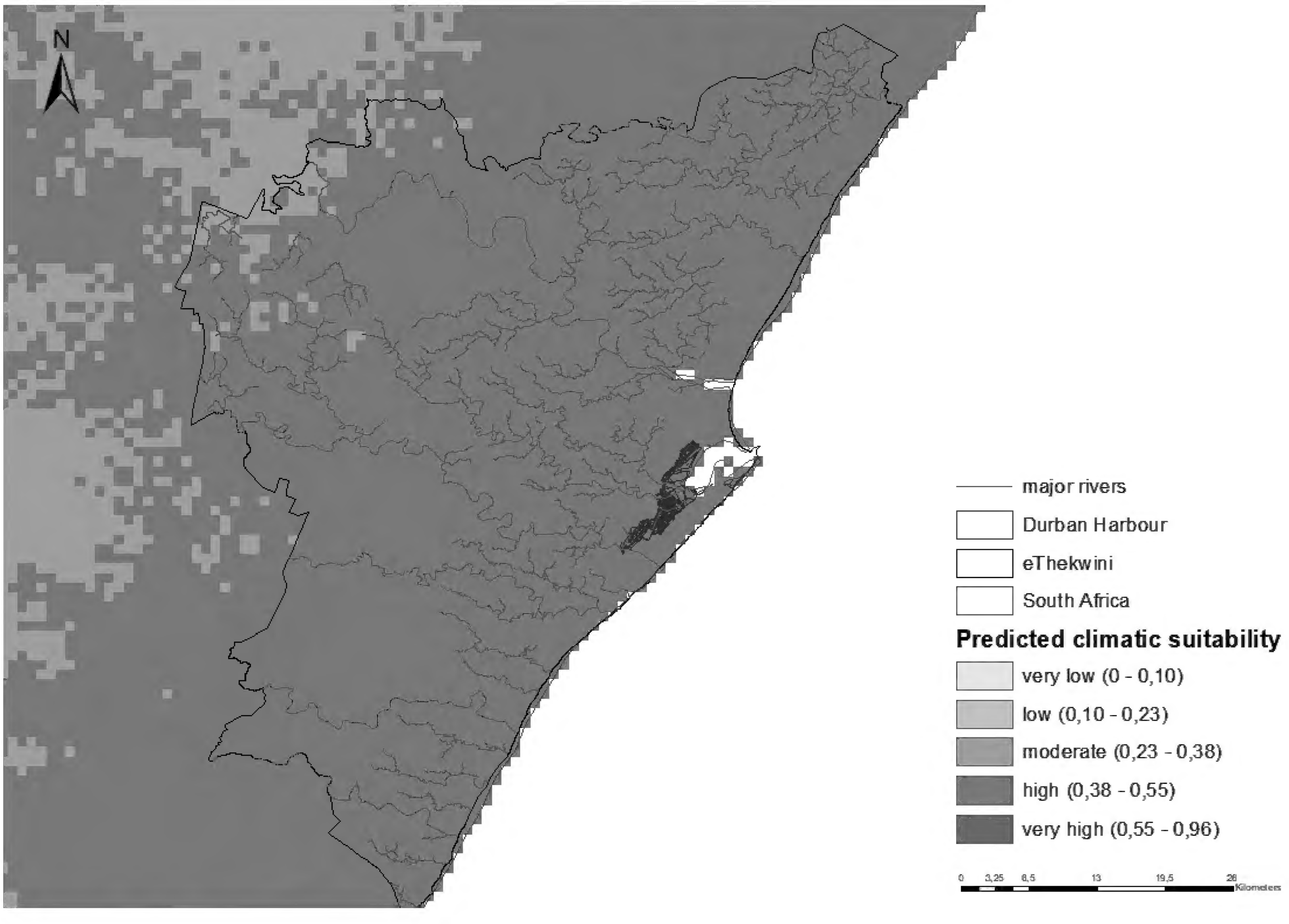

Figure B2. Predicted climatic suitability for *C. echinatus* in Durban. The model is moderately accurate in predicting climatic suitability (0.812 ± 0.008 – AUC±SD). Predicted climatic suitability is indicated using a colour scale (darker shades indicate higher predicted suitability). Even though pathways of introduction for this species could not be identified with certainty, the potential points of introduction and first naturalisation (i.e. where to monitor) for *C. echinatus* in Durban are indicated.

Pathways of introduction: Unknown

Potential points of first introduction: The Durban harbour

Habitat and Land uses: *Cenchrus echinatus* favours temperate and tropical zones. This species is usually found in open lands, cultivated fields, along roadsides and coastal environments and waste places.

Habitats present in Durban: Yes

Potential sites of first naturalisation: The Durban harbour and adjacent beach environments and sand dunes

Box 3. Pathways of introduction, preferred habitats, potential entry points, sites to monitor, and climatic suitability for *Lithobates catesbeianus*.

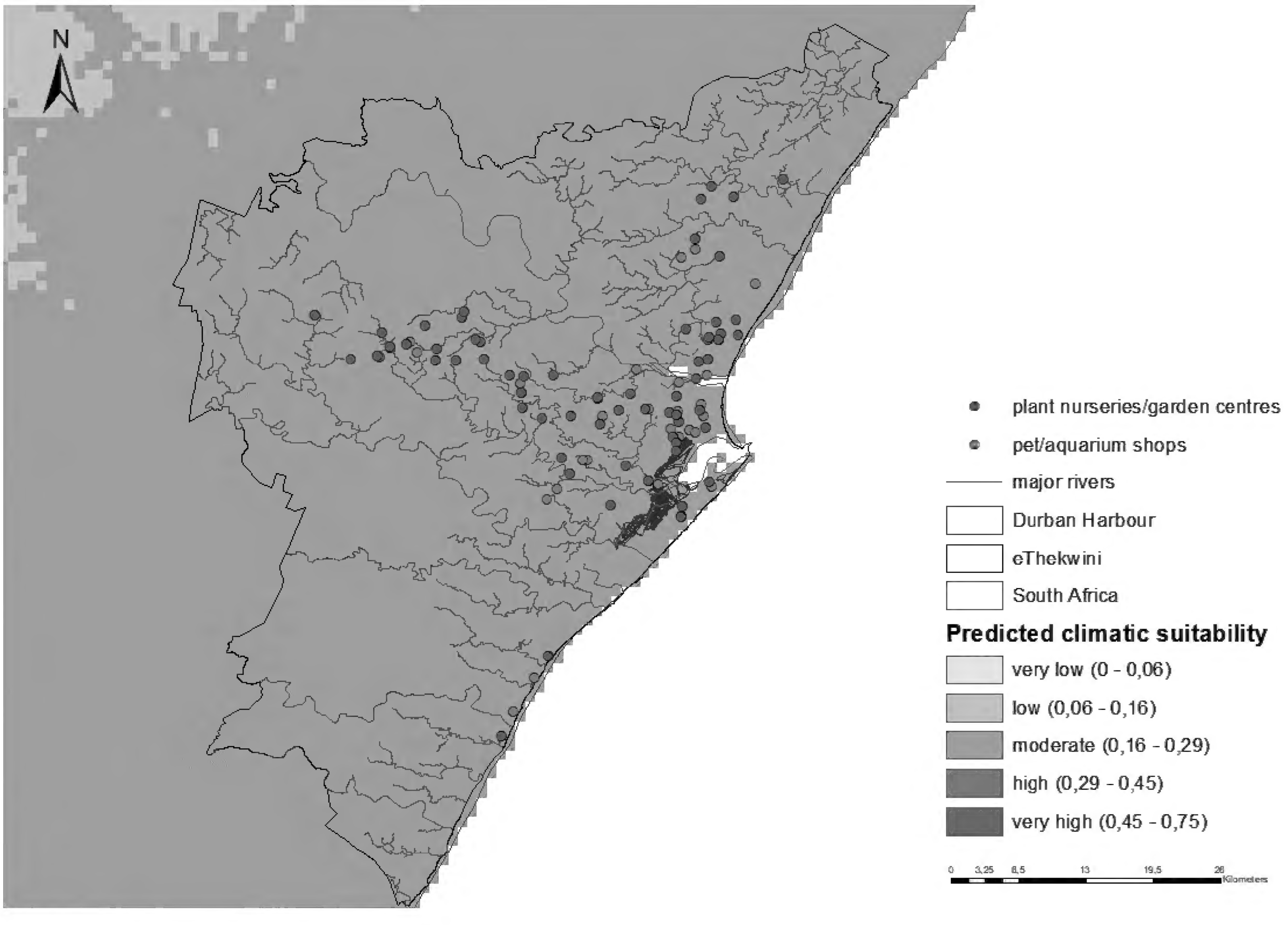

Figure B3: Predicted climatic suitability of *L. catesbeianus* in Durban. The model is moderately accurate in predicting climatic suitability (0.791 ± 0.005 – AUC±SD). Predicted suitability is indicated using a colour scale (darker shades indicate higher predicted suitability). Also indicated are the potential points of first naturalisation (i.e. priorities for monitoring) for *C.echinatus* in Durban.

Pathways of introduction: Biological control, landscape; floral and faunal improvement, release in use for nature, aquaculture (food source), ornamental purposes

Potential points of first introduction: The Durban harbour, pet and aquarium shops

Habitat and Land uses: *Lithobates catesbeianus* prefers warm, moist environments and requires permanent, shallow and still bodies of water. This frog species usually occupies ponds, swamps, streams and irrigation ditches

Habitats present in Durban: Yes

Potential sites of first naturalisation: Major river systems, especially those adjacent to potential points of introduction (pet and aquarium shops)

Box 4. pathways of introduction, preferred habitats, potential entry points, sites to monitor, and climatic suitability for *Solenopsis invicta*.

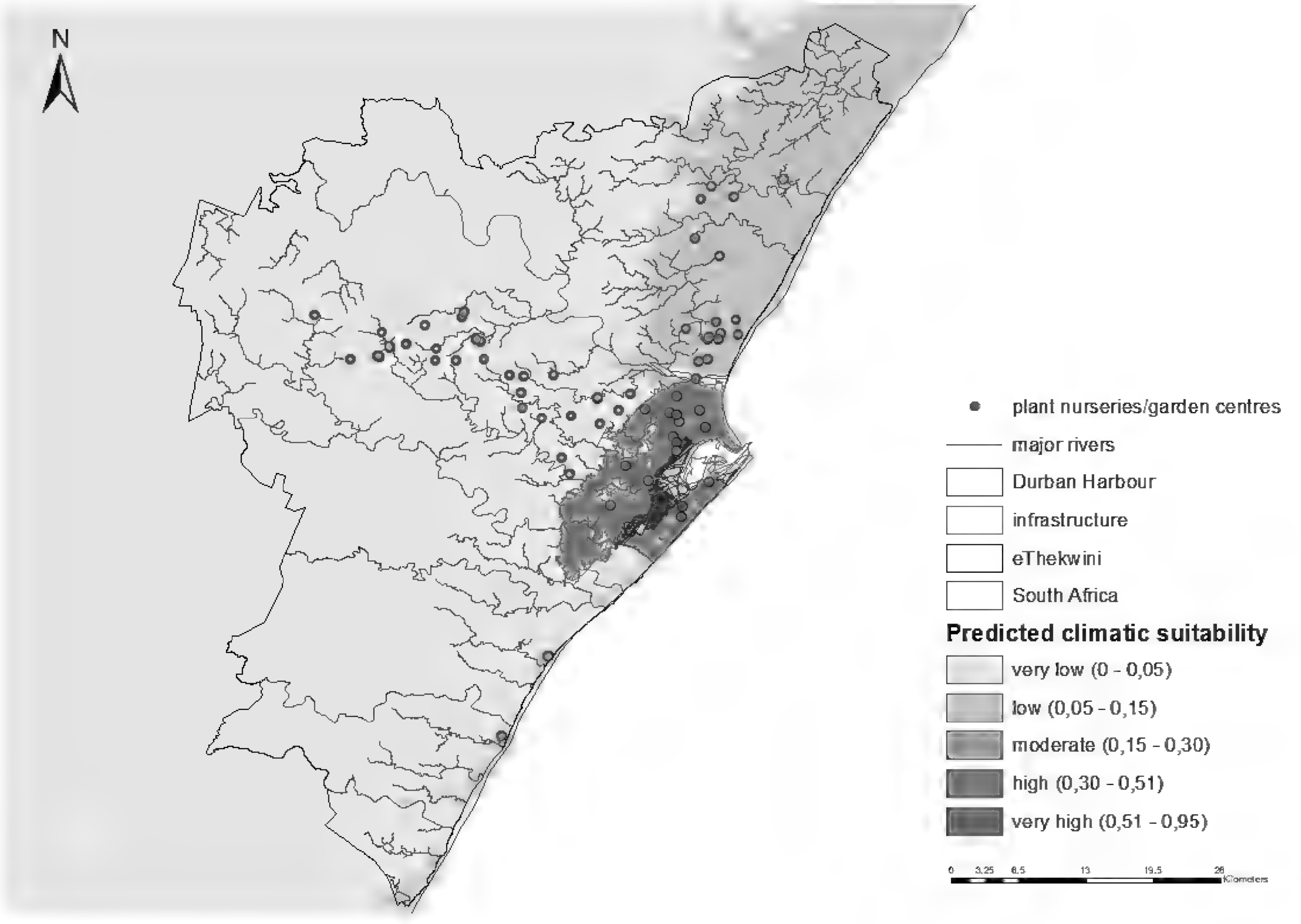

Figure B4: Predicted climatic suitability of *S. invicta* in Durban. The model is highly accurate in predicting climatic suitability (0.961 ± 0.006 – AUC±SD). Predicted suitability is indicated using a colour scale (darker shades indicated higher predicted suitability). Also indicated are the potential points of introduction and fist naturalisation to monitor for *S. invicta* in Durban.

Pathways of introduction: Contaminated nursery material, translocation of machinery and equipment, organic wood packaging

Potential points of first introduction: The Durban harbour, plant and nursery material

Habitat and Land uses: *Solenopsis invicta* can occupy a wide variety of habitats and can become dominant in altered habitats. This ant species is found in disturbed or developed forests or on trails near buildings

Habitats present in Durban: Yes

Potential sites of first naturalisation: The Durban harbour and adjacent built infrastructure, plant nurseries and garden centres and surrounding natural environments linked to major river systems

operating characteristics (see Table 1 for details). However, the patterns of predicted climatic suitability varied for each of the species. The *L. catesbeianus* (Figure B3) and *C. echinatus* (Figure B2) models (moderately accurate performance) showed a uniform climatic suitability for these species across the city, with *C. echinatus* having a higher predicted climatic suitability than *L. catesbeianus*. The *A. philoxeroides* (Figure B1 – highly accurate model performance) model showed the highest predicted climate suitability along the coastline of eThekwini decreasing to the north-west of the city. The *S. invicta* (Figure B4 – highly accurate model performance) model showed a relatively low climatic suitability; however, the most important regions for *S. invicta* were the northern regions and the coastline of the city (see Table 1 for details).

Additionally, we superimposed pet and aquarium shops, nurseries and garden centres, the major river systems and the Durban Harbour data with the climatic suitability models (see Boxes 1–4). From the sixty plant nurseries and garden centres in eThekwini, eighteen were located adjacent to major rivers, while seven were located adjacent to the Durban Harbour. Climatic suitability for *C. echinatus* and *L. catesbeianus* (Boxes 2–3) was found to be uniform across the city; therefore, all points of introduction are likely to be sites of first naturalisation. The highest predicted climatic suitability for *A. philoxeroides* (Box 1) was found along the coast of eThekwini in which 34 plant nurseries and garden centres were located. We found 23 plant nurseries and garden centres located in low climate suitability regions for *S. invicta* (Box 4). We found 29 pet and aquarium shops within eThekwini, 13 of which were located near the major river systems while eight were located near the harbour. Nineteen pet and aquarium shops were located in the regions of highest predicted suitability for *A. philoxeroides*, while 17 were

Table 1. List of species for which predictive models were developed, the bioclimatic predictors used to develop each model, and the percentage contribution of each predictor to the model.

Species	Bioclimatic Predictors selected (% contribution to model)	Model Performance (AUC ± Standard Deviation)
Alternanthera philoxeroides	Mean diurnal range (10), Mean temperature of the warmest month (17), Precipitation seasonality (21), Precipitation of the warmest quarter (9), Precipitation of the coldest quarter (54)	High accuracy (0.929 ± 0.007)
Cenchrus echinatus	Mean temperature of the warmest quarter (25), Precipitation of seasonality (34), Precipitation of the wettest quarter (44), Precipitation of the driest quarter (7)	Moderate accuracy (0.812 ± 0.008)
Lithobates catesbeianus	Mean diurnal range (4), Temperature seasonality (44), Maximum temperature of the warmest month (21), Precipitation of the warmest quarter (3), Precipitation of the coldest quarter (38)	Moderate accuracy (0.791 ± 0.005)
Solenopsis invicta	Mean diurnal range (13), Maximum temperature of the warmest month (28), Precipitation of the wettest month (20), Precipitation of the driest month (45), Precipitation seasonality (4)	High accuracy (0.961 ± 0.006)

located in the highest predicted suitability for *S. invicta*. One pet and aquarium shop was located within the built infrastructure adjacent to the Durban Harbour; hence this was highlighted as an important potential point of introduction for *A. philoxeroides*, *L. catesbeianus* and *S. invicta*.

Discussion

While watch lists and prohibited lists are beneficial in highlighting species to monitor, the lists often consist of numerous species, across a variety of taxa (e.g. the NEMBA prohibited species list – 553 targeted species; Faulkner et al. 2014 – 400 watch list species). The selection criteria used in this study (Figure 1) allow for these lists to be narrowed down in the context of a specific urban setting, to provide priority targets for incursion response. We recommend that three of the species identified (*Alternanthera philoxeroides*, *Lithobates catesbeianus* and *Solenopsis invicta*) be targeted for contingency planning in eThekwini, e.g. through the production of awareness material to improve passive surveillance, consideration of active surveillance through a monitoring scheme, and the development of incursion response plans so that if they are detected, there is no delay before action is taken (Wilson et al. 2017). Consideration should also be given to planning for the fourth species, *Cenchrus echinatus*, although the priority will be to first identify if and where it is likely to be introduced.

The Convention on Biological Diversity (CBD) Aichi Target 9 requires that pathways of introduction be identified and prioritised for management efforts (UNEP, 2011). In this study, we identified likely sites of first naturalisation as priorities for incursion response efforts. We identified three important potential introduction points: the Durban Harbour; pet and aquarium stores; and nursery and garden centres. Each of the species used in this study were linked to one of these potential introduction points. The potential sites of first naturalisation identified in this study were all found to be in close proximity to the Durban harbour and the major river systems in the city, indicating that these sites are important for monitoring efforts.

Identifying the pathways facilitating the introduction of alien species is important for preventing alien species introductions. However, not all pathways of introduction are operational in all cities. By identifying the pathways which facilitate alien species introductions, priorities can be assigned to species with the potential of being introduced to the particular region of interest. In this study we were able to eliminate the species *Vulpes vulpes* (red fox) because the pathways facilitating its introduction (hunting in the wild and fur farms) are not operational in eThekwini. By contrast, the pathways which facilitate the introduction of *C. echinatus* are unknown. Therefore, determining if, how, and where the species is likely to be introduced to the city should be a key area for future applied research.

The Durban Harbour was identified as an important potential introduction point as well as a site to monitor for the introduction of *A. philoxeroides* and *S. invicta*. The pathways facilitating the introduction of these species are linked to the

harbour. *Alternanthera philoxeroides* is primarily introduced through ship ballast and as a stowaway on ship cargo (Burgin et al. 2010), while *S. invicta* is introduced on organic wood packaging. These species can thrive in highly transformed habitats; therefore we also recommend the adjacent infrastructure to the harbour as sites for monitoring efforts. *S. invicta* is known to have negative ecological, economic and social impacts (Tang et al. 2013). Ecologically, this species is known to reduce native invertebrate and vertebrate communities through predation (Allen et al. 2004, McGlynn 1999, Holway et al. 2002). Furthermore, this species dominates altered habitats such as those present in cities, where *S. invicta* has an affinity to electrical equipment (Morrison et al. 2004). This ant is considered to be one of the most destructive invasive ant species (Lowe et al. 2000, Ascune et al. 2011). *S. invicta* also has negative social impacts and poses a threat to humans as the venom from *S. invicta* stings can cause severe allergic reactions (Solley et al. 2002). Box 4 shows that predicted climatic suitability for *S. invicta* coincides with land use in the city; this is potentially problematic for the human population. Therefore, we recommend that this species should be a priority target for strategic prevention efforts.

The river systems adjacent to potential point of introduction in the municipality were also identified as important sites to monitor. *Alternanthera philoxeroides* (Julien et al. 1995) and *Lithobates catesbeianus* (da Silva and Filho 2009) are found in aquatic habitats such as rivers, along flood plains, in lakes and dams. *Alternanthera philoxeroides* is primarily an aquatic plant but can invade terrestrial environments such as agricultural areas (Burgin et al. 2010). *Alternanthera philoxeroides* can reproduce vegetatively to form new infestations from broken plant material and often forms fragile mats covering water bodies. *Lithobates catesbeianus* is introduced primarily through intentional introductions for faunal improvement to landscapes, ornamental purposes and through aquaculture as a food source (Measey et al. 2017). *Lithobates catesbeianus* has high fecundity and environmental plasticity and is known to grow relatively large in size, ensuring their survival in a variety of habitats including disturbed environments (da Silva and Filho 2009, Akmentins and Cardozo 2010). Furthermore, bullfrogs are potential vectors of diseases to native amphibians (Ficetola et al. 2007, Eskew et al. 2015). Box 1 (*A. philoxeroides*) and Box 3 (*L. catesbeianus*) both show potential points of introduction in close proximity to the major river systems in the municipality. Both of these species are considered to be prolific invaders with potentially devastating impacts (*A. philoxeroides* – Burgin and Norris 2008, Chen et al. 2013, *L. catesbeianus* – Lowe et al. 2000). Both *A. philoxeroides* (Burgin and Norris 2008, Burgin et al. 2010, Basset et al. 2010, Clements et al. 2011) and *L. catesbeianus* (Ficetola et al. 2007, da Silva and Filho 2009, da Silva et al. 2009) are capable of spread via natural dispersal once introduced and will be at best difficult to manage (Padayachee et al. 2017), especially because the likelihood of these species establishing throughout the city is high (Boxes 1, 2). We recommend both of these species as targets for strategic prevention efforts in eThekwini.

Invasions are, of course, often unpredictable and context dependent. Therefore the prioritisation here should only be one small part of an overall biosecurity strategy (Wil-

son et al. 2017). The most effective methods for detection (e.g. traps or visual inspections) and the mix between passive and active surveillance (Hester and Cacho 2017) will depend on the biology of the organism. Similarly, it is important to understand the context of the invasion, going beyond whether pathways still operate to consider factors that might limit invasions (e.g. is there a strong mechanistic reason , such as biotic resistance, for expecting that the uniquely insular invasions discounted here will not become invasive in eThekwini?). It will be vitally important to continue general surveillance efforts and create and maintain capacity to respond to surprises. However, by identifying species that are known to be problematic elsewhere in the world, that are likely to establish in eThekwini, and that are likely to be introduced, at least part of the detection and response efforts can be prioritised. It also helps eThekwini meet its legal requirements to address the threat posed by future biological invasions.

Even though this study focuses on eThekwini, the procedures used here represent a practical method to assign priorities for preventing the introduction of alien species. The methodology used in this study has merit for assigning priorities to a variety of taxa, such as this study (invertebrates, plants and vertebrates), or single taxa studies. Online databases such as CABI ISC, GBIF, GISD and GRIIS make alien species information required for utilising this methodology readily accessible. The accessibility of information and adaptability of the methodology used in this study makes the protocol feasible. However, there are many ways in which the protocol can be improved. For example, occurrence data sourced from online databases are often plagued with inconsistencies (e.g. validity of location points and taxonomy). The use of expert opinion in determining the validity of these data is a potentially beneficial improvement to this prioritisation tool. The procedures used in this study can further be improved quantitatively through additional analyses which will assess how pathways of introduction contribute to invasiveness (e.g. frequency analysis tests) of the target species as well as the contribution of potential introduction points to invasiveness (e.g. landscape level analysis) of target species. The advantage of the technique presented here is that it focuses on likely known threats and ensures that appropriate measures are put in place to deal with them.

Conclusion

Prioritisation is a fundamental component of effective strategic prevention strategies targeting the introduction of alien species to new regions (Reaser et al. 2008, Essl et al. 2011, McGeoch et al. 2016, Padayachee et al. 2017, Pergl et al. 2017). The selection criteria used in this study provide decision makers with an easy way to identify where to focus resources to target incursions that have a high likelihood of occurring and resulting in substantial negative impacts. Implementing prioritisation schemes that consider all three aspects (species, pathways, and sites) (Wilson et al. 2017) allows decision makers to target monitoring efforts where the risk of particular invasions is highest. Additionally, integrating prioritisation schemes, such as in this study, allows decision makers to focus resources on species which poses a greater risk of invasion and impact.

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